

**INTEGRATED FREQUENCY SELECTABLE RESONANT  
COUPLING NETWORK AND METHOD THEREOF**

**FIELD OF THE INVENTION**

5           This invention relates in general to communication equipment and more specifically to a method, apparatus, and integrated circuit for frequency selectable coupling of signals within such equipment.

**BACKGROUND OF THE INVENTION**

10           Communications equipment and networks and methods of coupling signals therein are known. As this communications equipment has become smaller the desire for ever-smaller, more efficient, less complex, and less costly coupling networks and systems has grown. More recently more of this communications equipment has been  
15           tasked with operating in multiple frequency bands. For example cellular phones or devices or handsets now routinely operate in two or more distinct frequency bands, such as 800 or 900 MHz as well as 1.8 and above GHz.

          It is known to provide multiple receiver front ends and multiple coupling networks to multiple mixers with each line up contributing its own frequency selectivity or filtering, however this is expensive in terms of cost and volume required  
20           within the equipment even when most or all of the respective components are integrated. One technique used for these multiple line ups includes a narrow band low noise amplifier transformer coupled to a mixer where the transformer is resonant with a capacitor for selectivity. It is known that resonating the transformer will provide filtering and using a varactor to tune this resonant frequency has been

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contemplated. However multiple lineups are required to cover multiple frequency bands.

Clearly a need exists for an integrated frequency selectable resonant coupling network and methods thereof suitable for use in integrated circuits adapted for

5 communications equipment.

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### SUMMARY OF THE INVENTION

This invention concerns various aspects of an integrated center frequency selectable resonant coupling network, a radio frequency (RF) receiver front end integrated circuit (IC) that uses an embodiment of the coupling network and is  
5 arranged and constructed for receiving signals in a plurality of frequency bands, and a method in an integrated circuit for processing signals in a plurality of frequency bands.

The integrated center frequency selectable resonant coupling network aspect of the invention includes an integrated coupling transformer having a secondary  
10 winding for coupling to a load and a primary winding for coupling to a source; a first integrated capacitive circuit controllably coupled across a one of the primary and the secondary windings and when so coupled operable to resonate with the integrated coupling transformer at a frequency in a first frequency band; and a second integrated capacitive circuit coupled across a second one that may be the same one of the  
15 primary and the secondary windings and when so coupled operable to resonate with the integrated coupling transformer at a second frequency in a second frequency band.

The radio frequency (RF) receiver front end integrated circuit (IC) aspect of the invention is arranged and constructed for receiving signals in a plurality of  
20 frequency bands. The IC includes a low noise amplifier (LNA) for amplifying an input signal within the plurality of frequency bands; a center frequency selectable resonant coupling network that further includes an integrated coupling transformer having a primary winding coupled to said LNA and a secondary winding a first integrated capacitive circuit controllably coupled across a first one of the primary and

the secondary winding and when so coupled operable to resonate with the integrated coupling transformer at a first frequency in a first one of the plurality of frequency bands; and a second integrated capacitive circuit coupled across a second one that may be the same as the first one of the primary and the secondary winding and when

5 so coupled operable to resonate with the integrated coupling transformer at a second frequency in a second one of the plurality of frequency bands; and a radio frequency mixer for down converting an output signal at the secondary winding within either the first or the second of the plurality of frequency bands to a base-band signal.

The method in an integrated circuit for processing signals in a plurality of

10 frequency bands aspect of the invention includes: providing an input signal within alternatively a first frequency band and a second frequency band; coupling the input signal to a primary winding of an integrated coupling transformer; controlling an integrated switched capacitor network that is coupled to the transformer to provide a coupling network that is alternatively and respectively resonant at a first frequency

15 within the first frequency band and a second frequency within the second frequency band to selectively provide an output signal at a secondary winding of the transformer; and down converting the output signal.

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### BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying figures, where like reference numerals refer to identical or functionally similar elements throughout the separate views and which together with the detailed description below are incorporated in and form part of the specification, 5 serve to further illustrate various embodiments and to explain various principles and advantages all in accordance with the present invention.

FIG. 1 depicts, in a representative form, a block diagram of a preferred embodiment of a radio frequency receiver integrated circuit according to the present invention;

10 FIG. 2 depicts, in a simplified schematic form, a preferred embodiment of an integrated frequency selectable resonant coupling network that is suitable for use in the FIG. 1 block diagram and in accordance with the present invention;

FIG. 3 illustrates in a more detailed schematic of the FIG. 2 coupling network according to a preferred embodiment of the present invention;

15 FIG. 4 shows a detailed schematic of a control portion of the coupling network of FIG. 3; and

FIG. 5 depicts a representative performance graph of an experimental version of the FIG. 3 coupling network.

**DETAILED DESCRIPTION OF PREFERRED EMBODIMENT**

In overview the present disclosure concerns methods and apparatus that enable communications equipment that provide services for users thereof. More particularly various inventive concepts and principles embodied in methods, apparatus, and integrated circuits (ICs) for frequency selectable coupling and processing of signals are discussed and disclosed. The communications equipment of particular interest are cellular devices or handsets or the like that must operate in multiple frequency bands and the frequency selectable coupling networks are advantageously used, for example, to individually couple signals within these multiple frequency bands to a common function. Such circumstances would be encountered, for example, in a cellular phone or handset that operates in the below 1 GHz cellular frequency band, for example GSM band between 925 – 960 MHz, but must also operate in the DCS and PCS frequency bands, respectively, 1.805 – 1.880 GHz and 1.930 – 1.990 GHz.

The instant disclosure is provided to further explain in an enabling fashion the best modes of making and using various embodiments in accordance with the present invention. The disclosure is further offered to enhance an understanding and appreciation for the inventive principles and advantages thereof, rather than to limit in any manner the invention. The invention is defined solely by the appended claims including any amendments made during the pendency of this application and all equivalents of those claims as issued.

It is further understood that the use of relational terms, if any, such as first and second, top and bottom, and the like are used solely to distinguish one from another entity or action without necessarily requiring or implying any actual such relationship

or order between such entities or actions. Much of the inventive functionality and many of the inventive principles are best implemented with or in various semiconductor circuits and processes. It is expected that one of ordinary skill, notwithstanding possibly significant effort and many design choices motivated by, for example, available time, current technology, and economic considerations, when guided by the concepts and principles disclosed herein will be readily capable of generating such circuits in accordance with the design rules of the appropriate semiconductor processes with minimal experimentation. Therefore further discussion of such circuits and processes, if any, will be limited to the essentials of the preferred embodiments all in the interest of brevity and minimization of any risk of obscuring the principles and concepts according to the present invention.

FIG. 1 depicts, in a representative form, a block diagram of a preferred embodiment of a radio frequency receiver integrated circuit (IC) 100 according to the present invention. This IC is preferably fashioned in a high speed process, such as Silicon Germanium bipolar or CMOS process suitable for integrating RF receiver front-end circuitry. The process would also preferably have multiple metal interconnections layers (3 or more) capable of implementing a highly-symmetric transformer function and capacitors exhibiting low parasitics for implementing an efficient switched capacitor network, for example, MIM (metal-insulator-metal) capacitors. This IC 100 is preferably a radio frequency (RF) receiver front-end integrated circuit (IC) that is arranged and constructed in an inventive and advantageous manner for receiving signals in a plurality of frequency bands, such as the 800 – 975 MHz band and the 1.8 to 2.0 GHz frequency band. The IC includes a low noise amplifier (LNA) for amplifying an input signal within the plurality of

frequency bands. Preferably a plurality (3 depicted) of LNAs 101, 102, 103 are each coupled to their respective feed circuits (generally known and not shown), such as, an antenna etc. and are optimized and operate, when enabled, to amplify signals within one of the plurality of frequency bands. These LNAs are relatively narrow band

5 LNAs each for amplifying one of a plurality of signals, each, respectively, within one of the plurality of frequency bands. In a preferred form this LNA or LNAs are known differential cascaded common-emitter LNAs. Theoretically any number of LNAs could be provided or included however, as one of ordinary skill will recognize, practical considerations such as number of IC I/O pins, circuit parasitics, layout

10 complexity, and chip size may result in an upper limit.

The LNA or LNAs in parallel are coupled to a center frequency selectable resonant coupling network 105. The network 105 is further coupled to a radio frequency mixer 107. The LNAs preferably provide a differential signal at the inputs 109, 111 of the network. The radio frequency mixer 107 operates to convert an

15 output signal from the network at 113, 115 that is within any one of the plurality of frequency bands to a base-band signal 121. While various forms of the mixer will operate, in the preferred embodiment this mixer is a known double balanced direct conversion mixer having a bandwidth of well over an octave. The mixer is further driven by a local oscillator signal (not shown) to provide the base-band signal at a

20 frequency equal to the difference between the frequency of the output signal (input signal to the mixer) and local oscillator signal.

This network 105 includes an integrated coupling transformer 113 having a primary winding 116 coupled to the LNAs and a secondary winding 118, optionally



including a fixed capacitor (nominally 75 fF and not explicitly shown) parallel coupled thereto, coupled to the mixer 107 and an integrated, preferably switched, capacitor network 119 that is controllably coupled, preferably using one or more integrated switches that are actively biased both on or shorted and off or open, across

5 one or both of these windings to cause the transformer to resonate at various frequencies within the plurality of frequency bands. The capacitor or capacitive network is here depicted as a plurality of series coupled capacitors that can individually be switched in parallel with the primary winding. The specifics and additional particulars of the coupling network 105 as well as capacitor network 119

10 will be discussed in further detail herein below.

However, it will be clear that the RF receiver front end IC is preferably arranged to couple a differential signal from the LNA(s) to the radio frequency mixer thereby rejecting common mode signals. The integrated coupling transformer is advantageously used in the preferred form to provide an impedance transformation

15 between the LNA and the radio frequency mixer, thereby improving a power match. This transformer is preferably implemented as a 6:2 transformer (3:1 ratio) where for every 6 turns on the primary there are 2 turns on the secondary winding. Thus the LNA that are relatively high impedance devices can be more closely power matched to the relatively lower impedance mixer. Furthermore by providing a center tap on

20 the primary winding or on the secondary winding biasing for, respectively, the LNAs or mixer can be facilitated without requiring additional inductors or the like. In sum in the preferred form the RF receiver front end IC 100 is particularly suited and arranged and can be used for selectively and alternatively coupling, from one relatively narrow band LNA to the radio frequency mixer, as amplified by the LNAs,

a first differential signal centered at a frequency that is less than 1 GHz and a second differential signal centered at a frequency that is greater than 1.8 GHz.

As a brief overview with a detailed discussion to follow, with reference to the additional figures, the IC 100 and coupling network 105, preferably, includes

5 frequency band or coarse frequency changing as well as frequency tuning integrated capacitive circuits as part of the capacitor network 119. Included is a first integrated capacitive circuit controllably coupled, again preferably by an integrated switch that is actively biased on and off, across one of the primary winding or the secondary winding and when so coupled operable to resonate with the integrated coupling

10 transformer at a first frequency; and a second integrated capacitive circuit coupled or controllably coupled across one of the primary winding or the secondary winding and when so coupled operable to resonate with said integrated coupling transformer at a second frequency. By coupling various combinations of the first and second integrated capacitive circuits across their respective windings the coupling network

15 and integrated coupling transformer will be caused to resonate at frequencies within the plurality of frequency bands. These combinations can include neither or both or either of the first and second integrated capacitive circuits. The RF receiver front end IC 100 may further include one or more (3 depicted) integrated capacitive circuits controllably coupled across the primary winding or the secondary winding that when

20 so coupled, effectively in parallel with one of the other, first and second, integrated capacitive circuits operate to fine tune or cause a more modest shift in, respectively, one of the frequencies where the transformer resonates.

These integrated capacitive circuits further include a control terminal for a control signal to control coupling of the integrated capacitive circuits across their

respective, primary or secondary winding. Each of these integrated capacitive circuits further include, respectively, a switch and corresponding capacitors that are carefully arranged to present a balanced differential load to a differential signal provided by the LNA or other differential signal source when the integrated

5 capacitive circuit is coupled across its respective winding as well as when the capacitive circuit is not so coupled. In the preferred form these integrated capacitive circuits each include, coupled across their respective primary or secondary a series circuit that includes a first capacitor in series with an integrated switch, preferably actively biased on or off, that is further in series with a second capacitor, where the

10 first capacitor and the second capacitor are arranged to be of equal value. The control terminal, not shown in FIG. 1 is operable to open or short the integrated switch. With this symmetrical circuit an actual layout of an IC can be organized such that differential loads presented to the differential signal are very closely matched even with respect to various parasitics.

15 The following description is provided with reference to the FIG. 2 depiction, of a simplified schematic of a preferred embodiment of an integrated frequency selectable resonant coupling network 105 that is suitable for use in the FIG. 1 block diagram. Elements in FIG. 2 that are identical or similar to the same elements in FIG. 1 are identified with like reference numerals. Thus the overall network 105, the

20 integrated coupling transformer 117 having a primary winding 116 for coupling to a source or signal, such as the LNA of FIG. 1, at inputs 109, 111 and a secondary winding 118, optionally including a fixed capacitor (not shown) parallel coupled thereto, suitable for coupling to a load, such as the radio frequency mixer of FIG. 1 at outputs 113, 115, and the integrated capacitive circuit 119 are shown.

Further included in the integrated frequency selectable resonant coupling network 105 and more specifically the integrated capacitor or capacitive network 119 is a plurality (2 shown) of frequency band changing integrated capacitive circuits 201 as well as a plurality (3 shown) of frequency tuning integrated capacitive circuits 203.

- 5 The band changing integrated capacitive circuits 201 includes a first integrated capacitive circuit 205 that is switched or controllably coupled across or in parallel with one of the primary winding and the secondary winding (depicted across primary). When this integrated circuit is so coupled it will operate and be operable to resonate with the integrated coupling transformer at a first frequency, preferably, in or
- 10 within one of the plurality of frequency bands. Additionally included in the band changing integrated capacitive circuits 201 is a second integrated capacitive circuit 207 that is coupled and, preferably, switched or controllably coupled across one of the primary winding and the secondary winding and when so coupled operable to resonate with the integrated coupling transformer at a second frequency in a second
- 15 one of the plurality of frequency bands. Note that additional band changing integrated capacitive circuits can be included if and as required to cover additional bands and band-width.

- Additionally the integrated center frequency selectable resonant coupling network 105 includes one or more (3 depicted) frequency tuning integrated capacitive
- 20 circuits 209, 211, 213 controllably coupled or switched across the primary winding as depicted or alternatively the secondary winding and when so coupled across one of the primary or the secondary windings, effectively in parallel with the first integrated capacitive circuit 205 and the second integrated capacitive circuit 207, operable to fine tune, respectively, one of the first and the second frequencies of resonance. Each

of the first, second, etc. integrated capacitive circuits 205 - 213 include, respective, control terminals 215 - 223 for application of a control signal in order to control coupling of the integrated capacitive circuits, respectively, across the primary winding or the secondary winding. In the preferred form this control terminal is the

5 gate lead of an NMOS transistor or switch. Further each of the integrated capacitive circuits includes a bias lead, respectively, 216 - 224 that is coupled to both the source and drain terminal of the NMOS device through large value (on the order of 20K to 100K ohm) resistors. This bias technique will be further discussed below with reference to FIG. 3 and 4.

10 More specifically each of the integrated capacitive circuits further include, respectively, a switch 231 - 239 and corresponding capacitors C5, C4, C3, C2, C1 that are arranged to present a balanced differential load to a differential signal provided by the source or LNA when the integrated capacitive circuit is coupled across the primary winding or the secondary winding as well as when the integrated

15 capacitive circuit is not coupled across the primary winding or the secondary winding. In particular in the preferred form the integrated capacitive circuits each include, coupled across the, respective primary or secondary winding, a series circuit that includes, respectively, a first capacitor C5 - C1 in series with the integrated switch 231 - 239 that is further in series with a second capacitor C5 - C1, where the

20 first capacitor and the second capacitor are arranged to be of equal value all as depicted. In the preferred circuit the capacitors have nominal values of C5=3.9pF (pico-Farad), C4=1.1pF, C3=0.86pF, C4= 0.26pF, and C1=0.175pF. In the preferred NMOS form when the control or gate terminal is brought to a high potential the bias lead will be brought to a low potential thus operating to short the integrated switch so

the two capacitors are coupled together in series with or through a low impedance path. When the control or gate terminal is brought to a low potential and the bias lead to a high voltage the integrated switch becomes essentially an open circuit having an impedance approximated by the large value resistor in series with each capacitor to a  
5 common potential or ground. Collectively this operates to present a balanced differential load including parasitic loads to the differential signal regardless of whether the switch is open or shorted. As a practical matter the integrated switches will need to be designed for reasonably low impedances relative to the capacitors they are coupling or shorting together.

10 The integrated center frequency selectable resonant coupling network 105 as above noted includes the integrated coupling transformer 117 and this preferably includes a center tap 241 on the primary winding and a center tap 243 on the secondary winding, where these center taps can facilitate biasing by providing a path for a DC bias current for, respectively, one of the source or LNAs and the load or  
15 mixer. As earlier noted by varying the turns ratio of the integrated coupling transformer it may be arranged to provide an impedance transformation between the source and the load, thereby improving a power match between the source and the load. The integrated center frequency selectable resonant coupling network 105 and constituent elements thereof is especially suited for frequency selective coupling a  
20 differential signal from the source to the load. In the preferred form the integrated center frequency selectable resonant coupling network 105 is arranged for selectively and alternatively coupling, from the source to the load, a first differential signal centered at a frequency that is less than 1 GHz and a second differential signal centered at a frequency that is greater than 1.8 GHz.

The reader will note that the integrated capacitive circuits have all been depicted as controllably coupled across the primary winding of the integrated coupling transformer. This is the approach used in the preferred embodiment where the primary side of the transformer is relatively high impedance since the source or

5 LNA used is relatively high impedance and the secondary side is relatively low impedance since the load or radio frequency mixer is relatively low impedance. By including the integrated capacitors on the higher impedance side of the transformer the capacitors can be relatively smaller thereby saving space, particularly given the large number of capacitors. Further more the integrated switches do not have to be as

10 low in impedance as they would if the capacitors were larger and thus lower in impedance at the frequencies of interest as would be the case on the secondary side of the transformer. On the other hand operating voltages will be higher on the higher impedance side of the resonant circuit. If for practical reasons, such as operating voltage constraints, layout convenience or otherwise or if the mixer utilized was

15 higher impedance than the source, one or more or all of the integrated capacitive circuits could be placed on the secondary side of the transformer. Additionally while all of the integrated capacitive circuits have been shown with a switch for coupling (or not coupling) the circuit to the primary winding, at least one of them such as the aforementioned optional fixed capacitor ,could always be coupled across one of the

20 windings. In this instance a capacitor that was the minimum value ever anticipated would be hard coupled to the relevant winding and the controllable integrated capacitive circuits would be activated or switched on to add capacitance and thus lower the frequency at which the transformer would resonate as desired. Also note that any or all or any combination of the controllable integrated capacitive circuits

may be coupled to their respective windings at any one time and if the values of the capacitors are judiciously chosen as here the resultant integrated frequency selectable network will be tunable throughout an extensive, octave plus, frequency range..

Referring now to FIG. 3 a more detailed schematic of an integrated center frequency selectable resonant coupling network 305 is depicted and will now be described. Like or similar elements from FIG. 2 are identified by like reference numerals. The integrated capacitive circuits 205 – 213 are depicted in representative form with some layout information as well as the nominal values for C5 – C1. The center tap 241 for the primary winding 116 is shown coupled to a supply voltage while the center tap 243 of the secondary winding 118 is made available for coupling to a mixer ground.

Referring to FIG. 4 the integrated capacitive circuit 209 is shown in further detail. Please note that this circuit is analogous for each of the other integrated capacitive circuits 205, 207, 209, and 211. The capacitive circuit 209 includes C3\_2 (nominally 869 femto-Farads) in series with integrated switch 235 ( preferably an NMOS transistor) further in series with C3\_1 that is nominally equal to C3\_2 all coupled across the primary winding of the transformer or specifically the input leads 109, 111. The integrated switch has a control terminal 219 connected to the gate lead of the switch. The drain and source leads of the integrated switch have resistors 401, 403 (nominally 20 to 100K ohms but closely matched) respectively coupled thereto and together to the bias lead 220. The integrated switch is actively biased on or off as follow. The control signal at the control terminal 219 is coupled to an inverter 405. Whenever the control signal goes high shorting or turning on the integrated switch the inverter output will go to ground 409 thus pulling the common terminal of the



resistors to ground as well as the source and drain through the large value resistors.

This will insure that the integrated switch is fully turned on and remains so regardless of the differential signal that may be applied. Conversely when the control terminal goes low the inverter output will go high or to the supply voltage<sup>407</sup> and apply a

- 5 high voltage to the drain and source again assuring the switch remains off or in a high impedance state regardless of the differential signal that is applied at the input leads.

Referring to FIG. 5, a representative performance graph of an experimental version of the FIG. 3 coupling network is shown and will be briefly discussed. FIG. 4 is a plot showing the gain of the integrated center frequency selectable resonant

10 coupling network versus frequency with different combinations of the integrated capacitive circuits enabled or shorted across the primary winding of the integrated coupling transformer. Higher loss is observed at lower frequencies due to the small size of the integrated transformer and thus low coupling at those frequencies, however this gain droop or drop can be compensated for in surrounding circuitry such

15 as the gain of the source or LNA or load or mixer. You will also note the large frequency range from below 800 MHz to nearly 2 GHz that is covered by the coupling network, thus validating the practical nature of the coupling circuit in using multiple LNAs but only one mixer. This is important as radio frequency mixers, because of the dynamic range they must cover and extreme linearity requirements, as

20 known are non-trivial circuits to implement in an integrated manner.

As a brief review a preferred method embodiment according to the present invention will be described. Basically this method is preferably implemented in the above described coupling network or RF IC. The method in an integrated circuit is for processing signals in a plurality of frequency bands and includes providing an

input signal within alternatively a first frequency band and a second frequency band; coupling the input signal to a primary winding of an integrated coupling transformer; controlling an integrated switched capacitor network that is coupled to the transformer to provide a coupling network that is alternatively and respectively

5 resonant at a first frequency within the first frequency band and a second frequency within the second frequency band to selectively provide an output signal at a secondary winding, optionally including a fixed capacitor parallel coupled thereto, of the integrated coupling transformer; and down converting the output signal to base band.

- 10 Preferably the step of providing includes providing a differential input signal and the step of controlling includes controlling an integrated switched capacitor network that at all times and in all states presents a balanced load to the differential input signal within the first frequency band and within the second frequency band. Controlling the capacitive network further includes controlling one or more integrated
- 15 switched capacitor networks or circuits that each, preferably includes a series circuit including a first fixed and integrated capacitor coupled to a controllable integrated switch and further coupled to a second fixed integrated capacitor that is arranged to be equal to the first capacitor. The series circuit is coupled across one of the primary winding or the secondary winding. Controlling the controllable integrated switch to
- 20 be one of a high impedance circuit and a low impedance circuit causes the coupling network to be alternatively resonant at the first frequency and the second frequency.

The processes and apparatus discussed above, and the inventive principles thereof are intended to and will alleviate problems caused by or resulting from prior art coupling networks where by different signals from multiple frequency bands were

received by multiple radio frequency line ups. Using the integrated frequency selectable resonant coupling network discussed and disclosed herein provides a number of advantages. For example the coupling network and surrounding functionality is entirely integrated in IC form. By selectively resonating the coupling

5 network by switching capacitive circuits across a coupling transformer, frequency selectable operation is achieved over an octave or more in frequency range and the band pass nature of the structure is advantageously used for rejection of far out spurious signals. The preferred differential form improves rejection of common mode signals and the transformer allows for an impedance transformation if needed,

10 DC level shift when needed, and facilitates biasing of source and load functions with the center tap arrangement. Using these principles and benefits of this coupling arrangement will simplify and lower costs for communications equipment thus facilitating connectivity for mobile individuals.

Various embodiments of methods, integrated circuits, and coupling apparatus

15 for selectively coupling a plurality of narrow band signals to a common wider band function so as to facilitate and provide for signal processing in an efficient and cost effective manner have been discussed and described. It is expected that these embodiments or others in accordance with the present invention will have application to communications equipment for wide area communications networks that provide

20 for mobility of their user or subscriber devices or units as well as wireless local area networks that are coupled to fixed WANS such as the PSTN or internet. Using the inventive principles and concepts disclosed herein advantageously allows or provides for low current drain and low part count communications equipment which will be beneficial to users and service providers a like.

This disclosure is intended to explain how to fashion and use various embodiments in accordance with the invention rather than to limit the true, intended, and fair scope and spirit thereof. The invention is defined solely by the appended claims, as may be amended during the pendency of this application for patent, and all equivalents thereof.

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